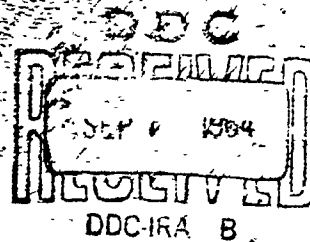


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Technical Report

Fourth Quarterly Progress Report:
Development of an HY-130/150
Weldment

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United States Steel

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FOURTH QUARTERLY PROGRESS REPORT: DEVELOPMENT OF AN HY-130/150 WELDMENT
(40.018-001) (31) (a-AS-NP-36) (S-10000-4)

By L. F. Porter, A. M. Rathbone, S. T. Rolfe, and K. E. Dorschu

Approved by J. H. Gross, Division Chief

Abstract

At the end of the third quarter (March 31, 1964), work on Bureau of Ships Contract No. NObs-88540, SR007-C1-01, Task 853, to develop a submarine hull weldment with a yield strength in the range 130 to 150 ksi (HY-130/150) indicated that a 5Ni-Cr-Mo-V steel and compatible filler metal meeting most of the requirements for an HY-130/150 weldment had been developed. Therefore, future work was to be concentrated on adapting the weldment to the requirements of shipyard submarine-hull fabrication.

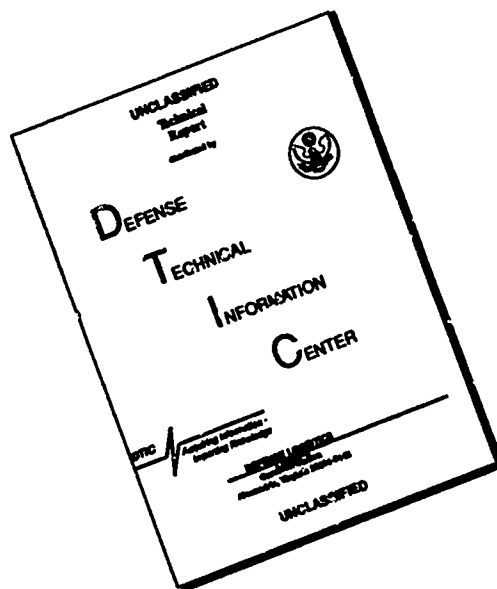
During the fourth quarter (~~April 1 to June 30, 1964~~), Laboratory development studies on the base metal were completed, and the results indicate that the 5Ni-Cr-Mo-V steel appears to be the optimum composition for an HY-130/150 steel. A second 80-ton electric-furnace heat, a 40-ton basic-oxygen-steelmaking (OSM) heat, and a 40-ton OSM vacuum-carbon-deoxidized heat of the 5Ni-Cr-Mo-V steel have been melted and are being evaluated. Ingots have also been cast from an OSM heat of the 5Ni-Cr-Mo-V steel for consumable-electrode remelting and for processing to a ring forging, and plans for producing castings and structural shapes have been formulated. The studies should indicate the suitability of the 5Ni-Cr-Mo-V steel for the various types of products required for submarine-hull construction, and should establish the composition ranges for the various 5Ni-Cr-Mo-V steel products.

Laboratory base-metal weldability studies, which defined composition limits for the 5Ni-Cr-Mo-V steel, have been completed. As anticipated, the heat-affected-zone crack susceptibility of the first production heat of the 5Ni-Cr-Mo-V steel was low, and its heat-affected-zone toughness was high. Covered-electrode and MIG weld metals of improved strength and toughness have been developed, and work to develop an all-position technique for depositing MIG filler metals is progressing on schedule. ()

A comprehensive program to evaluate the plastic-fatigue and fracture-toughness properties of 5Ni-Cr-Mo-V weldments has been planned, and 2-inch-thick plates of the 5Ni-Cr-Mo-V steel are being formed under shipyard conditions to confirm predictions on cold formability and to establish the effects of cold forming on mechanical properties.

If progress continues at the present rate, 5Ni-Cr-Mo-V steel products and a compatible filler metal should be available for the fabrication of a prototype structure during the third quarter of 1965.

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Introduction

During the period April 1 to June 30, 1964, work has continued on Bureau of Ships Contract No. NObs-88540, SR-007-01-01, Task 853, to develop a submarine-hull weldment with a yield strength in the range 130 to 150 ksi (HY-130/150). The status of the program as of March 31, 1963, including work in progress, was summarized in the third quarterly report.^{1)*} Most of the studies that were in progress at that time have been completed or significantly advanced during the fourth quarter. The detailed results of these studies have been described in seven individual reports, which are summarized in the present report. In addition, the present report describes the activities that are currently in progress or planned for the immediate future to develop an HY-130/150 weldment.

BASE-METAL DEVELOPMENT

During the past quarter work has been completed on (1) the effect of composition (variations in C, Mn, Si, Cr, Mo, and Al) on the properties of 5Ni-Cr-Mo-V steel, (2) the effect of carbon content on the hardenability and mechanical properties of 5Ni-Cr-Mo-V steel and (3) an evaluation of miscellaneous experimental HY-130/150 steels. These studies and two studies that have been completed but not formally reported—(1) the effect of strong nitride formers and deoxidizers and (2) the development of a Ni-Cr-Mo steel with higher Ms temperature—complete the work planned under General Studies,

*See References.

Major-Element Studies, and Minor-Element Studies (S-11100, S-11200, and S-11300) of the PERT Work Breakdown Structure, and show that the 5Ni-Cr-Mo-V steel is the most promising steel for an HY-130/150 weldment.

In Production-Size Development (S-11400) of the 5Ni-Cr-Mo-V steel, work in progress on composition adjustments (effect of variation in composition within the composition limits), melting practice (electric-furnace, basic-oxygen steelmaking process (OSM), basic-oxygen steelmaking process in combination with vacuum carbon deoxidation, and vacuum-consumable-electrode remelting) and processing variables (the effect of variation in crossrolling ratios and the effect of stress relieving).

To anticipate the development of specifications (S-11600), sample forging and castings of the 5Ni-Cr-Mo-V steel are being evaluated.

Work Completed

Evaluation of Miscellaneous Experimental HY-130/150 Steels²⁾

As part of the development of an HY-130/150 weldment, a number of experimental steels were evaluated, the properties of which were not reported earlier because they did not fall within the scope of previous reports. The steels consisted of three Mn-Ni-Cr-Mo steels, three 5-1/4- to 7-1/2-percent-nickel steels, four 5Ni-Cr-Mo steels, and two HY-80 steels.

The evaluation of the twelve steels indicated that none was particularly attractive as an HY-130/150 steel, and that each steel exhibited one or more shortcomings, such as inadequate hardenability, low strength,

poor notch toughness, or lack of sufficient resistance to softening on tempering. However, the studies did show that a reduction in the carbon, manganese, and/or sulfur content significantly improved the notch toughness of the 5Ni-Cr-Mo steels. However, compensating alloy additions must be made to offset the loss in hardenability when carbon and manganese are reduced.

Effect of Composition Variations on the Properties of 5Ni-Cr-Mo-V Steels³⁾

Previous studies have indicated that a 5Ni-Cr-Mo-V steel containing, in percent, 0.10 C, 0.75 Mn, 0.25 Si, 5.0 Ni, 0.5 Cr, 0.5 Mo and 0.07 V is very promising as an HY-130/150 steel. The effects of large variations in the composition were investigated during the development of the 5Ni-Cr-Mo-V steel. However, additional information was required to establish the carbon and alloy specification ranges for production melting of the 5Ni-Cr-Mo-V steel. Therefore, four composition modifications of a 5Ni-Cr-Mo-V steel containing 0.10 percent carbon and three modifications of a 5Ni-Cr-Mo-V steel containing 0.15 percent carbon were investigated. The results are summarized in Figure 1.

Among the 0.10 percent carbon steels, the standard 5Ni-Cr-Mo-V steel and a high-manganese, low-silicon (0.9% Mn, 0.04% Si) modification exhibited the best combination of yield strength (140 to 150 ksi) and notch toughness (80 to 120 ft-lb at 0 F). Severe embrittlement occurred when the chromium content was increased to 1.25 percent, and a general loss in toughness resulted when aluminum was eliminated.

Increasing the carbon content of the 5Ni-Cr-Mo-V steel from 0.10 percent to 0.15 percent increased the yield strength (after appropriate tempering) from the 130/150 ksi range to the 150/165 ksi range, but the notch toughness at 0 F was decreased to the range of 50 to 90 ft-lb. At the higher carbon content, the notch toughness was somewhat improved when the manganese and silicon content were reduced.

The results indicate that the standard 5Ni-Cr-Mo-V steel (0.10%C) is the best composition for a steel having a yield strength of 140 to 150 ksi and exceptional notch toughness. An 0.15 percent carbon 5Ni-Cr-Mo-V steel also exhibits good notch toughness at yield strengths of 150 to 165 ksi.

Effect of Carbon on the Hardenability and Mechanical Properties of 5Ni-Cr-Mo-V Steel⁴⁾

Previous Laboratory studies have shown that the 5Ni-Cr-Mo-V steel is extremely promising as an HY-130/150 steel. Therefore, a Laboratory study was initiated to establish the carbon range within which the desired properties of the 5Ni-Cr-Mo-V steel can be obtained. Seven Laboratory 5Ni-Cr-Mo-V steels containing 0.05 to 0.27 percent carbon were evaluated to establish the carbon-ordering range for the 5Ni-Cr-Mo-V steel as an HY-130/150 steel and to determine the potential of the 5Ni-Cr-Mo-V steel as an HY-180/210 steel.

The results, summarized in figure 2, show that an average yield strength of about 140 ksi should be obtained in 1/2-inch-thick, water-quenched plates at a carbon content of about 0.045 percent, but that a minimum carbon

content of about 0.085 percent should be specified to obtain similar properties at the midthickness of 4-inch-thick, water-quenched plates. Therefore, an ordering range of 0.09 to 0.13 percent carbon is recommended for the 5Ni-Cr-Mo-V steel to insure the desired strength, toughness, and weldability for an HY-130/150 steel.

In the tempering range 900 to 1200 F, none of the steels investigated exhibited a yield strength of 180 ksi. The high-carbon steels from the present study and other experimental steels are being evaluated at lower tempering temperatures to determine their potential as HY-180/210 steels.

Work in Progress

Composition-Adjustment Studies

A series of twenty-seven 300-pound vacuum-melted heats has been made in a statistically designed program to determine the effect of variations in manganese, nickel, chromium, and molybdenum on the properties of the 5Ni-Cr-Mo-V steel. In addition, three heats containing a lower than normal vanadium content (0.04 percent V instead of the usual 0.07 percent V) have been included in this study to investigate the advisability of specifying lower vanadium contents. The results of this program will be used to determine how composition variations within the established melting range will affect the hardenability and mechanical properties of the 5Ni-Cr-Mo-V steel and will provide the information required to specify different ordering ranges for different plate thicknesses from 1/2 through

about 6 inches if there appears to be an advantage in such a procedure. The design of the program is summarized in Table I.

Melting-Practice Studies

Electric-Furnace Process. A second 80-ton electric-furnace heat (No. X53588) of 5Ni-Cr-Mo-V steel was produced on April 12, 1964. The carbon, manganese, nickel, chromium, and molybdenum contents of this heat were held near the high end of the composition range to determine the effect of a "high-side" composition on the hardenability and mechanical properties of this steel. Plates 1/2, 5/8, 3/4, 1, 1-1/2, 2, and 3-3/8 inches thick were produced from the heat. In addition, a 5-1/4-inch-thick slab section was produced to investigate the hardenability of the steel. The chemical composition and tensile properties of 3/4-, 1-, and 2-inch-thick plates that will be used for extensive evaluation by the Laboratory and various Naval laboratories are given in Table II.

Of possible importance in design and in the specification of minimum yield strength are the results of the compression tests. These tests indicated that at a tensile yield strength of 147 to 148 ksi the compressive yield strength was 157 to 160 ksi.

Basic-Oxygen Steelmaking Process. A 40-ton basic-oxygen steel-making process (OSM) heat (No. 6Z1237) was melted and teemed into a 32- by 57-inch slab ingot and a 28-inch-diameter ingot on June 1, 1964. The chemical composition of the heat is given in Table III. Plates of 1/2-, 1-,

2-, and 4-inch thicknesses have been rolled from this heat and are now being evaluated. The evaluation is expected to help determine the feasibility of producing high-quality 5Ni-Cr-Mo-V steel by the OSM process.

Vacuum-Consumable-Electrode Remelting. One of the ingots cast in the aforementioned OSM heat (No. 6Z1237) was a 28-inch-diameter ingot weighing 24,000 pounds. Arrangements are now being made to vacuum-consumable-electrode remelt this ingot. Comparison of the properties of plate rolled from the remelted ingot with those of plate produced from the original OSM heat should indicate the extent to which vacuum-consumable-electrode remelting can upgrade the quality of the OSM material.

Vacuum Carbon Deoxidation. A 40-ton OSM heat (No. 6Z1242) was subsequently vacuum carbon deoxidized in a ladle-to-ladle degassing unit and teemed into a 32- by 57-inch slab ingot and two 25- by 25-inch ingots on June 10, 1964. The chemical composition of the vacuum-carbon-deoxidized OSM heat is given in Table III. The ladle analyses indicated that the carbon and phosphorus contents were slightly higher than the maximum specified when ordering the heat. However, the analysis is believed to be close enough to that desired to warrant an evaluation of the product, and the evaluation will provide additional information on the hardenability, notch-toughness, and weldability of the 5Ni-Cr-Mo-V steel when the carbon content is somewhat higher than optimum.

Processing Variables

Studies on the effect of stress relieving on the properties of 5Ni-Cr-Mo-V and HY-80 steels and on the effect of various cross-rolling ratios on the properties of the 5Ni-Cr-Mo-V steel that were described on the third quarterly progress report¹⁾ are now being completed and will be reported during the next quarter.

Evaluation of Forgings and Castings

Production of a Sample Forging. One of the 25- by 25-inch ingots cast from OSM heat No. 6Z1242 is being forged to a 41-inch-outside-diameter by 29-inch-inside-diameter ring (wall thickness of 6 inches) approximately 20 inches long. The processing of the ingot to the ring, inspection of the ring by sonic testing, and evaluation of the mechanical properties of tangential, longitudinal, and radial specimens taken at several locations should provide the information required to determine the forgeability of the 5Ni-Cr-Mo-V steel. This information will be used to recommend forging specifications.

Production of Sample Castings. Sample castings in the form of 1- by 6- by 6-inch plates and a 4- by 12- by 12-inch plate have been produced from Laboratory air-induction-melted heats of the 5Ni-Cr-Mo-V steel and are being evaluated. Macroetch sections of the castings indicate that they are sound. Mechanical properties are being determined on portions of the castings homogenized at 1700 F, 1850 F, or 2000 F for 8 hours, water-quenched,

and then reaustenitized at 1500 F for 2 hours, water-quenched, and tempered. The results of the macroetch studies, the homogenization studies, and studies of the variations in mechanical properties at various locations within the castings should indicate whether alteration of the 5Ni-Cr-Mo-V steel composition will be necessary for castings. The information will also be useful in recommending casting specifications.

Work Planned

As a part of the study of melting processes, plans are now being made to produce an 80-ton vacuum-degassed electric-furnace heat of the 5Ni-Cr-Mo-V steel.

To demonstrate the ability to produce structural sections of the 5Ni-Cr-Mo-V steel and to evaluate the mechanical properties of such sections, plans are being made to roll typical structural shapes from steel produced either in the planned vacuum-degassed electric-furnace heat or from the remaining 25- by 25-inch ingot from the vacuum-carbon-deoxidized OSM heat (No. 6Z1242). These studies and the work in progress will determine what additional work must be undertaken to complete the base-metal development of the 130/150 ksi weldment.

JOINING DEVELOPMENT

During the past quarter, work has been completed on (1) the evaluation of the weldability of production plates of the 5Ni-Cr-Mo-V experimental HY-130/150 steel, (2) a second study of the effects of

composition on the properties of covered-electrode weld metals, (3) the effects of coating formulation on the toughness of covered-electrode weld metal, and (4) an extension of the study of the effects of shielding gas on interrupted-arc MIG welding. In addition, the study of the effect of the manganese and nickel contents of the base metal on the properties of the 130/150 weld metal was completed. The results of this latter study were inconclusive in that the experimental weld metals did not exhibit yield strengths in the desired 130/150 ksi range; and therefore, further work on this study will not be undertaken.

Work Completed

Base-Metal Weldability

Weldability of Production 130/150 ksi Yield-Strength 5Ni-Cr-Mo-V Steel-I⁵). Previous Laboratory studies indicated that a steel containing 0.10 percent carbon, 0.75 percent manganese, 5 percent nickel, 0.50 percent chromium, 0.50 percent molybdenum, and 0.07 percent vanadium would exhibit extremely attractive properties for 130/150 ksi yield-strength hull plates. Therefore, an 80-ton heat of 5Ni-Cr-Mo-V steel was produced for extensive evaluation. Part of this evaluation consisted of a two-phase welding study that comprised (1) an investigation of the base-metal weldability by determining the weld-heat-affected zone toughness, transformation characteristics, and crack susceptibility and (2) an evaluation of the fabricability

of the steel in heavy sections. The first phase of the welding study was recently completed. The results indicate that the 5Ni-Cr-Mo-V steel has adequate hardenability to form a martensitic weld-heat-affected-zone microstructure for a practical range of welding conditions, Figure 3. Results of Charpy V-notch impact tests of simulated weld-heat-affected-zone microstructures indicate that the weld-heat-affected-zone toughness of the 5Ni-Cr-Mo-V steel is excellent. For the various heat-affected-zone regions tested, the energy absorption at 0 F ranged from 80 to 102 ft-lbs, Figure 4. The results of laboratory restraint-cracking tests indicate that the 5Ni-Cr-Mo-V steel possesses a low susceptibility to weld-heat-affected-zone cracking. Compared with HY-80 steel, the 5Ni-Cr-Mo-V steel appeared to be as good as an HY-80 steel that had previously exhibited a low susceptibility to cracking in large fabrication-type restraint-cracking tests.

Generally, the results of the present work indicate that the 5Ni-Cr-Mo-V steel has excellent welding characteristics. Such observations were expected inasmuch as the results of several laboratory welding and base-metal studies had been used to define the composition limits within which a Ni-Cr-Mo-(V) steel would exhibit an optimum balance of weldability and other required base-metal properties.

Filler-Metal and Joining-Technique Development

Covered-Electrode Filler Metals—Alloying Elements⁶⁾. Results of a previously reported¹⁾ study of covered electrodes indicated that weld

metals containing 0.06 percent carbon, 2.0 percent manganese, 2.0 percent nickel, and 0.5 percent molybdenum would exhibit yield strengths as high as 141 ksi with good toughness and soundness. The present study was undertaken to attempt to increase the yield strength of the previously studied covered-electrode weld metal by increasing the nickel, manganese, and/or chromium contents. The results of mechanical-property tests of eight experimental covered-electrode weld metals, Table IV, indicate that an increased yield strength can be achieved, but with some loss in tensile ductility and toughness compared with the previously studied covered electrodes. Several of the present higher yield-strength weld metals will be deposited by using electrodes made with high-purity core wires and coating ingredients to determine whether improved tensile ductility and toughness can be achieved.

Covered-Electrode Filler Metals - Coating Formulation. To determine the effects of coating formulation on the toughness of the previously described¹⁾ covered-electrode weld metals, twelve experimental AWS Class xxxl8 electrodes were deposited by using the same procedures that were used in the previous alloying-element studies. The results of Charpy V-notch impact tests, Table V, show that most of the weld metals exhibited impact properties similar to those of the control weld metal. The elimination of ferrotitanium (electrode number AA-099) appeared to exert a significant beneficial effect, particularly at low temperatures. Therefore,

ferrotitanium will be eliminated from the coatings of future experimental covered electrodes. In addition, future electrodes will be made with low-phosphorus and low-sulfur core wires.

MIG All-Position Procedures. Results obtained late in the third quarter indicated that a more extensive determination of the effects of shielding gas on interrupted-arc MIG welding should be undertaken. Therefore, the study was extended to include about 30 additional combinations of argon, helium, carbon dioxide, and oxygen in the form of 1) argon - carbon dioxide, 2) helium - carbon dioxide, 3) helium-rich argon - carbon dioxide, 4) argon-rich helium - carbon dioxide, and 5) argon-helium-oxygen mixtures. Generally, the results of tests employing out-of-position welding at different levels of current and voltage indicate that the argon - carbon dioxide mixtures and the helium-rich argon - carbon dioxide mixtures produce the most desirable arc characteristics, penetration, and weld-metal fluidity.

Work In Progress

Base-Metal Weldability

The status of programs previously described in quarterly progress reports is as follows:

Development of Small-Scale Restraint-Cracking Test. To complete the correlation between the laboratory cruciform specimen and the new small-scale specimen, the crack susceptibility of the 32 steels from the previously reported⁷⁾ statistical program is being evaluated with the small-

scale specimen. Test plates have been machined, and the specimens are being welded.

Statistical Program on Heat-Affected-Zone Cracking. The experimental work on the program to estimate the effects of chromium, molybdenum, and vanadium on the crack susceptibility of Ni-Cr-Mo-V steels has been completed. These data, along with the data obtained from the previously described⁷⁾ statistical program are currently being analyzed statistically.

Evaluation of 5Ni-Cr-Mo-V Steel. As described in the present report, the investigation of the base-metal weldability of the 5Ni-Cr-Mo-V steel by determining the weld-heat-affected-zone toughness, transformation characteristics, and crack susceptibility has been completed. The evaluation of the fabricability of the steel in heavy sections is currently in progress. This latter evaluation combines (1) large-size restraint-cracking tests, (2) tension, bend, and impact tests of 2-inch-thick weldments, and (3) gas-cut and plasma-cut bend tests.

Filler-Metal and Forming-Technique Development

MIG Major-Element Study. Eighteen experimental filler metals have been deposited and the weldments radiographed. Three of the 18 weld metals exhibited transverse cracks whereas the remaining ones were sound. The mechanical-properties of 8 of the weld metals have been determined, and specimens from the remaining ones are being machined. The yield strength

of the first 8 weld metals ranged from 132 to 144 ksi, and the Charpy V-notch energy absorption (+30 F) of these weld metals ranged from 74 to 115 ft-lbs.

Covered-Electrode Filler Metals - Alloying Elements. A series of 7 compositions of covered-electrodes has been prepared to determine the effects of silicon, molybdenum, and vanadium on the mechanical properties of the deposited weld metal. The weld metals have been deposited and mechanical-property-test specimens are currently being machined.

Development of Filler-Metal-Cracking Test. A new test has been designed that will produce an almost constant longitudinal strain in the weld metal at any time immediately after welding. The test consists of a 1/2-inch-thick bead-welded specimen that is bent by impact loading at selected strain levels. Currently, the final version of the test equipment is being constructed.

Work Planned

During the next quarter, several studies of the effects of welding procedures on the properties of 5Ni-Cr-Mo-V weldments will be initiated. Specifically, these studies are designed to (1) define the limits of plate thickness and preheat temperature within which suitable mechanical properties and soundness can be achieved, (2) determine the effects of stress relieving on mechanical properties, and (3) determine the relation between weld cracking and preheat and interpass temperature.

STRUCTURAL EVALUATION

During the past quarter a laboratory drop-weight bulge test was developed in which weldments can be biaxially strained (1:1) at relatively high loading rates to produce deformations similar to those observed in the explosion-bulge test. In addition, laboratory studies on the formability of HY-130/150 steels were completed and forming studies under submarine-yard conditions have been initiated.

Low-cycle plastic-fatigue results are being obtained on the 5Ni-Cr-Mo-V steel and a specimen has been developed for evaluating the plastic fatigue of weldments. Preliminary results of corrosion tests (both laboratory and field tests) on the 5Ni-Cr-Mo-V steel are being obtained.

Work Completed

Development of a Drop-Weight Bulge Test—1⁸)

The explosion-bulge test is used by the Navy to evaluate the capacity of weldments to deform under high-strain 1:1 biaxial loading. This test is one of the primary acceptance tests for submarine-hull weldments. However, the explosion-bulge test does not lend itself to laboratory screening of experimental weldments. Therefore, the Laboratory initiated a program to develop a laboratory test in which plate specimens could be 1:1 biaxially strained at relatively high loading rates to produce deformations similar to those observed in the explosion-bulge test plates.

Results of extensive experimentation indicate that the deformation distribution observed in explosion-bulge test plates can be simulated in a 1/2-inch-thick plate if a 14-inch-square test specimen is placed on top of a 9-inch-inside diameter anvil and impacted by a 5-1/2-inch-diameter hemispherical striker. The striker transmits an energy of 20,000 ft-lb to the plate through aluminum pads that distribute the strain throughout the plate bulge. A photograph of the drop-weight-bulge striker and anvil is shown in Figure 5.

To study the surface strain distribution during successive drops of the bulge striker, a 10-per-inch photogrid was applied to the tension surface of a 5Ni-Cr-Mo-V plate (yield strength approximately 150 ksi). Strains were measured along both center lines after each drop, and the strain distribution after drops 1, 3, 5, 7, 10, and 12 is shown in Figure 6. The true strains ($\ln \frac{L}{L_0}$) along both the N-S center line and the E-W center line (see sketch in Figure 6) were in excellent agreement and indicated that the test specimen was 1:1 biaxially strained.

Edge views of the plate after various drops are shown in Figure 7. The maximum surface strains corresponding to drops 1, 3, 5, 7, 10, and 12 were about 0.08, 0.11, 0.14, 0.17, 0.19, and 0.20 inches per inch, respectively. Thus, two items should be noted: (1) a single drop developed a 1:1 biaxial surface strain of about 0.08 inches per inch (thickness reduction of about 13 percent), a value that is apparently high enough to

screen experimental weldments; and (2) up to about 7 drops, the incremental strain per drop (about 0.03 inches per inch) was fairly constant, which indicates adequate machine capacity to deform 1/2-inch-thick plates at this strength level.

Formability of Experimental HY-130/150 Steels⁹⁾

Previous studies indicated that bend tests in conjunction with tension tests could be used to predict the formability of experimental HY-130/150 steels. Therefore, additional Laboratory studies were initiated on steels having yield strengths of 92 to 169 ksi to establish correlations between bend-test results and tension-test results.

The results of plane-strain bend tests on 1/4- and 3/8-inch-thick specimens showed that the bend angle depends on the geometry of the test setup (mandrel radius and span opening) and thus is not a broad indicator of formability. However, onset of surface cracking was found to depend on the true surface strain of the bend specimen regardless of the test setup, as shown in Figure 8. Thus, true surface strain, which can be conveniently determined from the specimen curvature (ratio of specimen thickness, h_0 , to outside bend radius, r_0), appears to be the best indicator of formability in the bend test.

The results of tension tests indicated that specimen curvature in the bend test correlated satisfactorily with reduction of area in the tension test as shown in Figure 9. Thus, formability by plane-strain bending can be

predicted from simple uniaxial tension tests. On the basis of a minimum reduction of area of 60 percent for the experimental HY-130/150 steels, minimum-inside-bend radii from 0.4 inch for 1/4-inch-thick plate to 7.1 inches for 4-inch-thick plate are predicted. These values, Table VI, indicate that the experimental HY-130/150 steels are more than capable of meeting the severe forming requirements for submarine hulls.

Work in Progress

Strength and Formability

The forming questionnaires that were forwarded to the Bureau of Ships for distribution to various submarine-fabrication yards have been received and are currently being evaluated. Information obtained from these questionnaires will be used in planning shipyard-forming studies on the effects of cold forming on the mechanical properties of the 5Ni-Cr-Mo-V steel as well as studies of current machine capacities.

As described in the Work-Completed section, the laboratory study on formability of HY-130/150 steels has been completed. On the basis of that work, a tabulation of the minimum predicted bend radii for HY-130/150 steels was prepared (Table VI). A program to verify these predicted limits for cold forming thick plates in plane strain is currently in progress.

Fracture

As described previously, the drop-weight bulge test appears suitable for evaluating the capacity of plates and weldments to deform under

high strain 1:1 biaxial loading. Preliminary drop-weight bulge tests of experimental weldments indicate that the test can be used successfully to screen laboratory weldments. To confirm this observation, HY-80 weldments will be fabricated by using welding procedures known to produce satisfactory and unsatisfactory weldments and the weldments will be drop-weight-bulge tested. Results of this series of tests should show whether the drop-weight bulge test can discriminate among weldments of different qualities.

In addition to screening laboratory weldments, the drop-weight bulge test may be suitable for establishing fracture-initiation and fracture-propagation characteristics for 1:1 biaxially loaded plain plates and welded specimens. Thus, both HY-80 and 5Ni-Cr-Mo-V steels will be drop-weight bulge tested at various temperatures, and the results will be correlated with nil-ductility-temperature (NDT), fracture-transition-elastic (FTE), and fracture-transition-plastic (FTP) characteristics determined from the explosion-bulge tests.

Explosion-bulge tests of 5Ni-Cr-Mo-V MIG weldments having under-, equal-, and over-matching weld metals are currently in progress.

Fatigue

Preliminary low-cycle plastic-fatigue test results for HY-80 steel and 5Ni-Cr-Mo-V steel are shown in Figure 10. The results are for smooth specimens tested in air at 10 to 20 cycles per minute. Results of an extensive investigation on HT, HY-80, HY-100, 150 ksi yield-strength, and 230

ksi yield-strength steels by M. R. Gross of the Marine Engineering Laboratory¹⁰⁾ are plotted in Figure 10 for comparison. The comparison shows that the strain range for the 5Ni-Cr-Mo-V steel is similar to that of HY-80 steel at cycles to failure less than 10^3 and is higher in the range 10^3 to 10^5 cycles.

The higher strain range in the region 10^3 to 10^5 cycles for the 5Ni-Cr-Mo-V steel would be expected because of its greater strength; however, since ductility is generally the controlling factor at low cycles, the strain range for the 5Ni-Cr-Mo-V steel would be expected to be lower than that for HY-80 in the region 10^2 to 10^3 cycles. This was not the case as shown in Figure 10. The excellent fatigue performance of the 5Ni-Cr-Mo-V steel at all cycle ranges is attributed to its good cleanliness.

So that the fatigue behavior of weldments can be evaluated, a welded fatigue specimen has been developed that can be tested on the low-cycle fatigue machine. The specimen is shown in Figure 11, and the essential features of the specimen are as follows:

1. The width is such that enough transverse restraint exists so that cracks initiate in the center rather than at the edges.
2. The specimen is tapered so that a uniform strain field exists over a 3-inch length (except as noted below). Thus, a transverse weld can be located in the center of a uniform strain field.

3. A large (6 inch) radius cut (0.10-inch-deep per side) is made to localize the failure in the vicinity of the weld. Strain-gage measurements taken along the length of the specimen show only a 5 percent variation in strain over the center 1-1/2 inches of the specimen.

4. Because of the uniform strain distribution, crack initiation does not occur in any particular location (base metal, heat-affected zone, or weld metal).

Fatigue tests of standard plain plate specimens and tapered plain plate specimens show no effect of specimen geometry. Thus, fatigue tests of weldments made with the specimen described in Figure 11 have recently been initiated.

Corrosion

The one-year sea-water exposure of HY-80 steel corrosion specimens and the six-month exposure of 5Ni-Cr-Mo-V steel corrosion specimens has been completed. Preliminary results show no stress-corrosion cracking of either steel, even though the specimens were cold-formed 16 percent and then stressed beyond the yield strength to accelerate failure. Complete evaluation of the specimens is currently in progress.

A laboratory study of the electrochemical properties of a 5 $\frac{1}{4}$ Ni-Cr-Mo-V steel, the 5Ni-Cr-Mo-V steel, and HY-80 steel in synthetic sea water has been completed and a report is being prepared.

Work Planned

In addition to continuing existing programs, emphasis will be placed on a large-scale evaluation of both MIG and covered-electrode 5Ni-Cr-Mo-V weldments and on an analysis of the formability of thick plates under actual submarine-yard conditions.

References

1. L. F. Porter, A. M. Rathbone, S. T. Rolfe, and K. E. Dorschu, "Third Quarterly Progress Report: Development of an HY-130/150 Weldment," Applied Research Laboratory Report 40.018-001(24), (S-10000-3), April 1, 1964.
2. D. S. Dabkowski, S. J. Manganello, and L. F. Porter, "Evaluation of Miscellaneous Experimental HY-130/150 Steels," Applied Research Laboratory Report 40.018-001(29), (S-11219), July 1, 1964.
3. S. J. Manganello and L. F. Porter, "Effects of Composition Variations on the Properties of 5Ni-Cr-Mo-V Steel," Applied Research Laboratory Report 40.018-001(30), (S-11324-1), July 1, 1964.
4. S. J. Manganello and L. F. Porter, "Effect of Carbon on the Hardenability and Mechanical Properties of 5Ni-Cr-Mo-V Steel," Applied Research Laboratory Report 40.018-001(25), (S-11324), July 1, 1964.
5. L. P. Connor, "Welding Characteristics of Production 5Ni-Cr-Mo-V Steel," Applied Research Laboratory Report 40.018-001(28), (S-13325), July 1, 1964.
6. K. E. Dorschu, "Development of HY-130/150 Covered-Electrode Weld Metals: Part II," Air Reduction Sales Company P&EDD-64-253, July 15, 1964.
7. A. M. Rathbone and B. K. Stewart, "Effects of Composition on Heat-Affected-Zone Cracking of Ni-Cr-Mo Steel Weldments—I," Applied Research Laboratory Progress Report 40.18-001(10), (S-12102), September 23, 1963.
8. S. T. Rolfe and L. P. Connor, "Development of a Drop-Weight-Bulge Fracture Test—I," Applied Research Laboratory Report 40.018-001(26), (S-13326), July 1, 1964.
9. S. T. Rolfe, "Formability of Promising HY-130/150 Steels," Applied Research Laboratory Report 40.018-001(27), (S-13204, S-13205), July 1, 1964.
10. M. R. Gross, "Low Cycle Fatigue of Materials for Submarine Construction," Naval Engineers Journal, Volume 75, No. 4, October, 1963, p. 783.

Table I

Statistically Designed Program - Composition-Adjustment StudyComposition Level of Elements Held Constant, percent

| Range | <u>C</u> | <u>P</u> | <u>S</u> | <u>Si</u> | <u>V*</u> | <u>Al**</u> | <u>N</u> |
|-------|--------------|--------------|--------------|--------------|--------------|----------------|--------------|
| | 0.09 0.11 | 0.010 Max | 0.010 Max | 0.20 0.30 | 0.06 0.08 | 0.020 0.030 | 0.010 Max |
| Aim | 0.10 | 0.006 | 0.006 | 0.25 | 0.07 | 0.025 | 0.006 |

Aim Composition*** Level of Elements Varied, percent

| <u>Level</u> | <u>Mn</u> | <u>Ni</u> | <u>Cr</u> | <u>Mo</u> |
|--------------|-----------|-----------|-----------|-----------|
| 1 | 0.25 | 4.5 | 0.25 | 0.25 |
| 2 | 0.50 | 5.0 | 0.50 | 0.50 |
| 3 | 0.75 | 5.5 | 0.75 | 0.75 |

*Three additional heats will be made containing 0.04 ± 0.01 percent V.

**Acid soluble

***Composition range for Mn, Ni, Cr and Mo is ± 0.05 percent.

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Table II

Chemical Composition and Mechanical Properties of
5Ni-Cr-Mo-V Steel from Heat No. 53588

| Plate Thickness, in. | Plate Number | Ladle Analysis, Percent | | | | | | | Yield Strength (0.2% Offset), ksi | Tensile Strength, ksi | Elongation in 2 inches, % | Reduction of Area, % | Charmy V-notch Energy Absorption at 32 F, ft-lb | Compressive Yield Strength (0.2% Offset), ksi |
|----------------------------|-----------------|-------------------------|------|-------|-------|------|------|------|---|-----------------------------|---------------------------------|----------------------------|---|--|
| | | C | Mn | P | S | Si | Ni | Cr | Mo | V | Al* | | | |
| | | 0.12 | 0.86 | 0.005 | 0.008 | 0.24 | 5.30 | 0.59 | 0.58 | 0.08 | 0.017 | | | |
| *Total aluminum. | | | | | | | | | | | | | | |
| 3/4 | 900340A1 | | | | | | | | | | | | 83 | 157 |
| | | | | | | | | | | | | | 61 | 160 |
| 1 | 090346A1 | | | | | | | | | | | | 87 | ND |
| | | | | | | | | | | | | | 74 | ND |
| 2 | 090337A1 | | | | | | | | | | | | 83 | ND |
| | | | | | | | | | | | | | 57 | ND |

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Table III

Chemical Composition of Steels Produced by the Basic-Oxygen Steelmaking Process
To Evaluate Melting Practices

| OSM Heat No. | Ingot Size, in. | Ladle Analysis, percent | | | | | | | | | |
|---------------------|--------------------|-------------------------|------|-------|-------|------|------|------|------|-------|-------|
| | | C | Mn | P | S | Si | Ni | Cr | Mo | V | Al |
| 6Z1237 | 32 by 57* | 0.10 | 0.78 | 0.006 | 0.010 | 0.24 | 4.88 | 0.49 | 0.54 | 0.08 | 0.04 |
| | 28 dia.** | 0.10 | 0.75 | 0.007 | 0.009 | 0.25 | 4.86 | 0.49 | 0.46 | 0.08 | 0.06 |
| 6Z1242 ⁺ | 32 by 57* | 0.15 | 0.79 | 0.012 | 0.010 | 0.25 | 5.06 | 0.60 | 0.54 | 0.077 | 0.025 |
| | 25 by 25*** | 0.15 | 0.79 | 0.012 | 0.010 | 0.27 | 5.08 | 0.61 | 0.58 | 0.079 | 0.028 |

*1/2-, 1-, 2-, and 4-inch-thick plate will be produced from this ingot.

**This ingot will be vacuum-consumable-electrode remelted

***This ingot will be used to produce a 6-inch-thick ring forging

[†]Heat 6Z1242 was vacuum carbon deoxidized.

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Table IV

MECHANICAL PROPERTIES OF EXPERIMENTAL HY 130/150 COVERED-ELECTRODE WELD METALS

| Electrode Number | Nominal Composition** | 0.505-Inch-Diameter Tension-Test Results* | | | | Charpy V-Notch Impact-Test Results* | | |
|---------------------|------------------------------|--|-----------------------------|---------------------------------|----------------------------|--|------|------|
| | | Yield Strength (0.2% Offset), ksi | Tensile Strength, ksi | Elongation in 2 Inches, % | Reduction of Area, % | Energy Absorption ft-lb | | |
| | | | | | | +75F | +30F | -60F |
| AA092 | 1.8 Mn, 2.5 Ni, 1.0 Cr. | 139 | 150 | 17.8 | 67 | 54 | 49 | 32 |
| AA086 | 2.0 Mn, 2.0 Ni, 1.25 Cr. | 143 | 154 | 16.5 | 51 | 48 | 44 | 28 |
| AA087 | 2.0 Mn, 2.0 Ni, 1.5 Cr. | 141 | 158 | 17.0 | 48 | 46 | 38 | 22 |
| AA088 | 2.0 Mn, 2.5 Ni, 1.25 Cr. | 140 | 158 | 12.5 | 34 | 47 | 41 | 26 |
| AA089 | 2.0 Mn, 2.50 Ni, 1.5 Cr. | 143 | 159 | 13.5 | 43 | 41 | 38 | 23 |
| AA090 | 2.0 Mn, 3.0 Ni, 1.0 Cr. | 144 | 158 | 8.5 | 16 | 45 | 41 | 28 |
| AA 317 | 2.0 Mn, 3.0 Ni, 1.5 Cr. | 148 | 165 | 5.0 | 9 | 34 | 25 | 12 |
| AA091 | 2.25 Mn, 2.25 Ni, 1.0 Cr. | 141 | 160 | 13.8 | 37 | 46 | 43 | 26 |

* All results are the average of two specimens unless otherwise noted.

** All weld metals contained approximately 0.06% carbon, 0.43% silicon, and 0.55% molybdenum.

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Table V

Impact Properties of Covered-Electrode Weld Metals Deposited
With Various Electrode-Coating Formulations

| Electrode Number | Coating-Formulation Change | Charpy V-Notch Impact-Test Results* | | | |
|---------------------|---|-------------------------------------|-------|-------------------------|-------|
| | | Energy Absorption, ft-lb | | Lateral Expansion, mils | |
| | | +30 F | -60 F | +30 F | -60 F |
| AA-026 | "Control" (Repeat of No. Z-7373) | 48 | 27 | 30 | 14 |
| AA-034 | K ₂ O Eliminated | 40 | 26 | 23 | 15 |
| AA-048 | Na ₂ O Eliminated | 43 | 29 | 25 | 17 |
| AA-039 | Coating Diameter Reduced (0.240-in. O.D.) | 43 | 30 | 25 | 16 |
| AA-040 | Coating Diameter Increased (0.260-in. O.D.) | 45 | 26 | 26 | 13 |
| AA-044 | CaCO ₃ Increased, CaF ₂ Decreased | 41 | 30 | 26 | 17 |
| AA-043 | CaCO ₃ Decreased, CaF ₂ Increased | 44 | 31 | 25 | 15 |
| AA-045 | ZrSiO ₄ Added | 40 | 26 | 25 | 15 |
| AA-046 | SrCO ₃ Added | 45 | 33 | 24 | 18 |
| AA-099 | FeTi Eliminated | 53 | 44 | 33 | 24 |
| AA-098 | All Ti Compounds Eliminated | 44 | 28 | 27 | 16 |
| AA-041 | Organics and Clay Eliminated | 48 | 35 | 28 | 18 |
| AA-049 | Pure Materials Used | 44 | 32 | 26 | 18 |

*Results are the average of three tests.

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Table VI

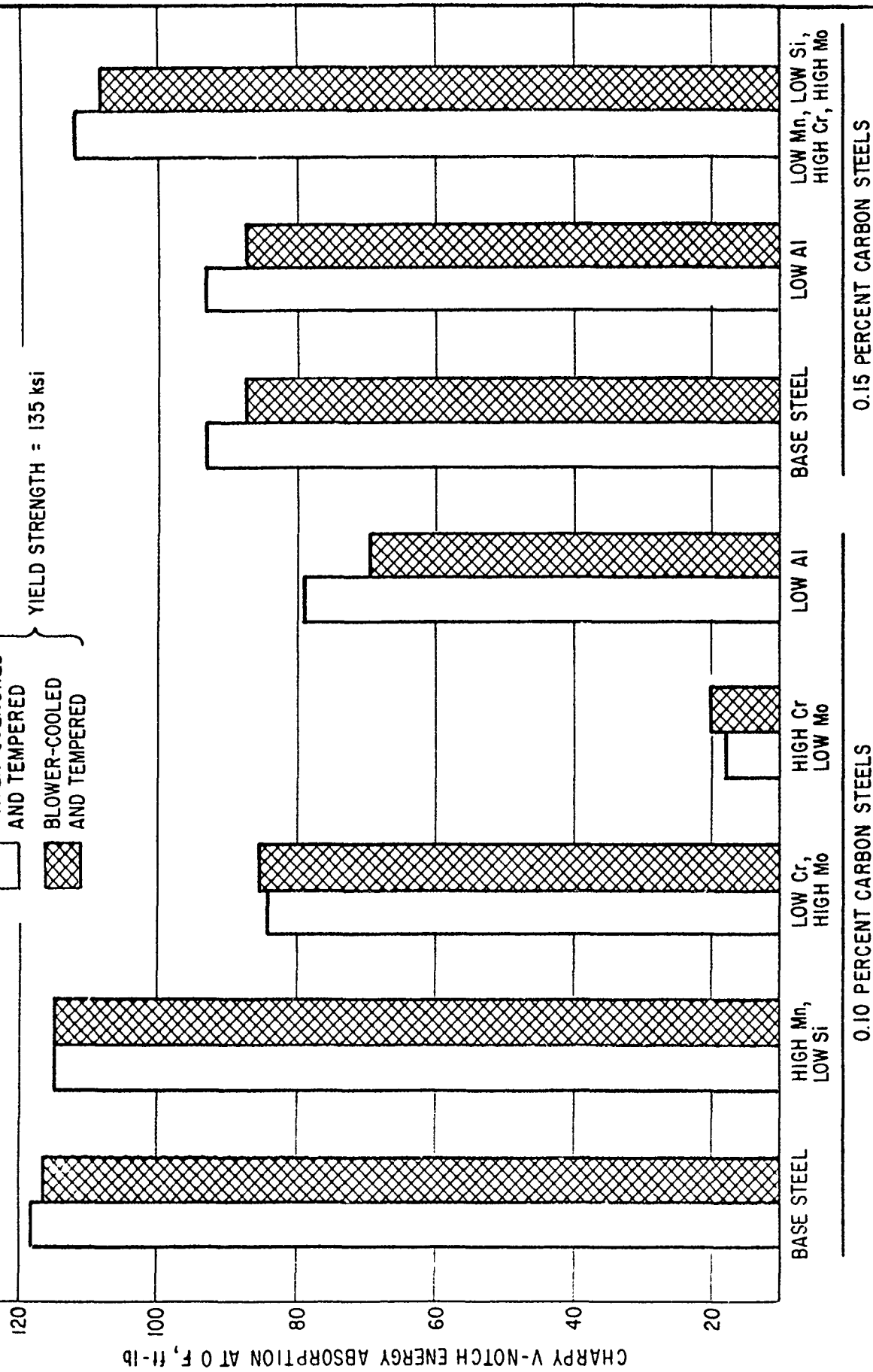
Minimum Predicted Bend Radii for Experimental HY-130/150 Steels (Based on
Minimum Reduction of Area of 60 Percent and Polished Surfaces)

| <u>Plate Thickness, inches</u> | <u>Predicted Minimum Inside Bend Radius, inches</u> |
|--|---|
| 1/4 | 0.4 |
| 1/2 | 0.9 |
| 1 | 1.8 |
| 1-1/2 | 2.7 |
| 2 | 3.6 |
| 2-1/2 | 4.5 |
| 3 | 5.3 |
| 3-1/2 | 6.2 |
| 4 | 7.1 |

(40.018-001) (31)

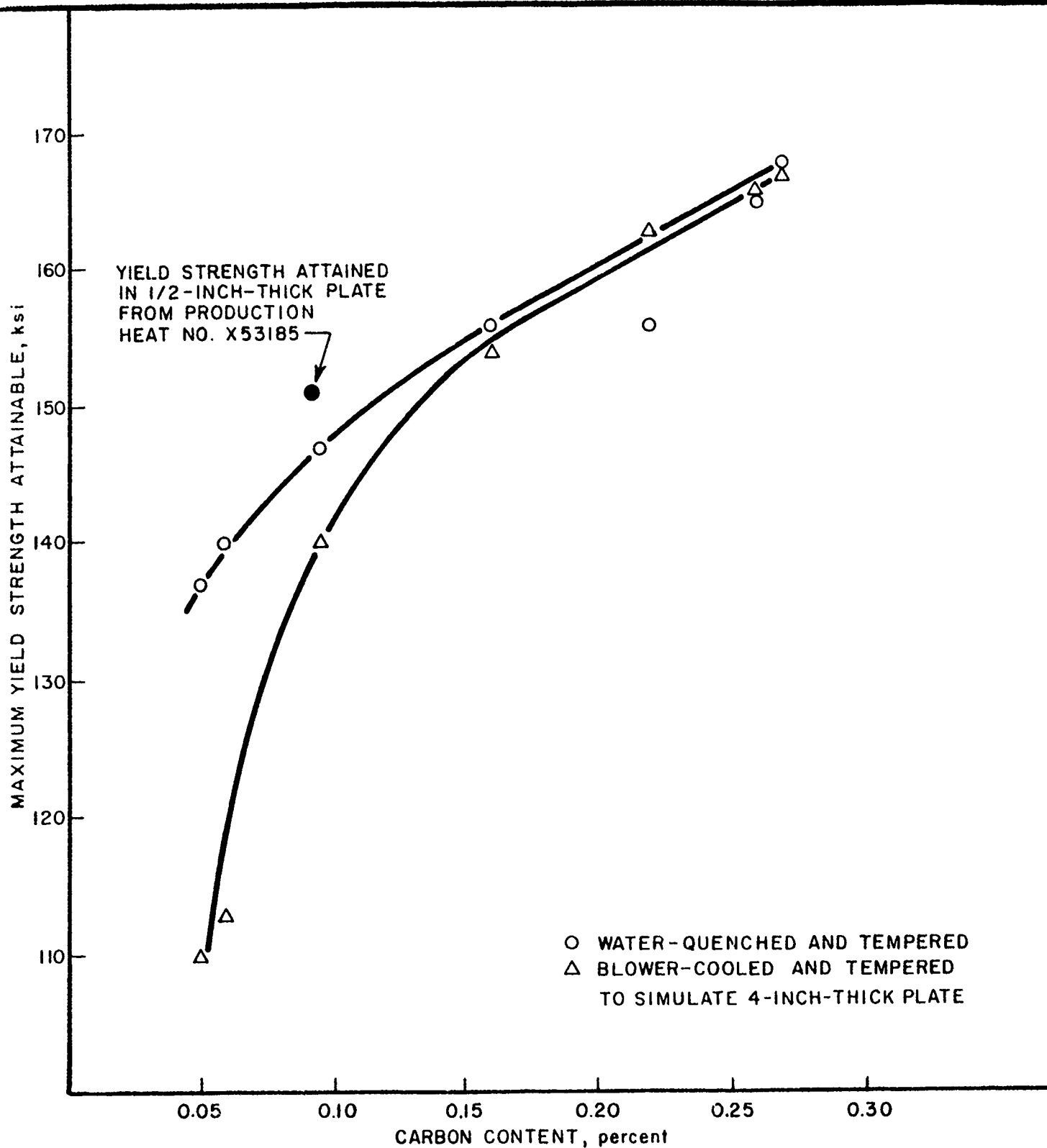
UNITED STATES STEEL

[] WATER-QUENCHED AND TEMPERED
 [] BLOWER-COOLED AND TEMPERED
 YIELD STRENGTH = 135 ksi



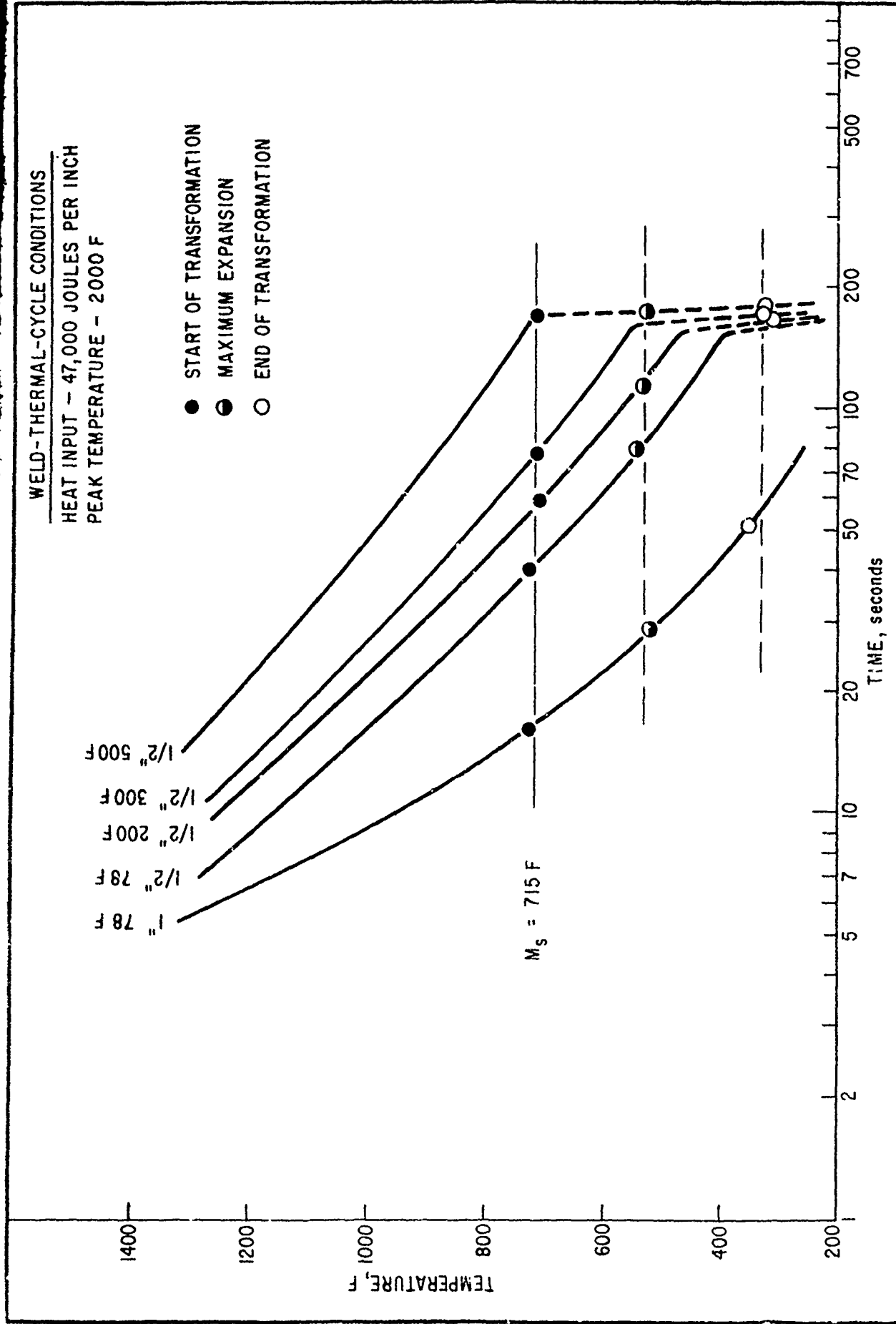
EFFECT OF COMPOSITION ON THE ENERGY ABSORPTION OF 1/2-INCH-THICK PLATES OF 5 Ni-Cr-Mo-V STEELS

| | | | | | |
|---------------------------|--|-------------------------------|-----------------------|--|-----------------|
| DRAWN BY M.M. | | CHK'D BY S.J.M. | APPROVED BY J.H.G. | UNITED STATES STEEL CORPORATION APPLIED RESEARCH PITTSBURGH, PA. | FIGURE NO. 1 |
| DRAWING NO. ARL 18-412 | | PROJECT NO. 40 018-001(31) | | | |
| | | DATE 7/9/64 | | | |



EFFECT OF CARBON CONTENT ON THE MAXIMUM ATTAINABLE YIELD STRENGTH IN
1/2-INCH-THICK PLATES OF 5Ni-Cr-Mo-V STEEL TEMPERED AT 900F OR HIGHER

| | | | | |
|--------------------------|--------------------|-------------------------------|--|--------------------|
| DRAWN BY G.A.Z. | CHK'D BY S.J.M. | APPROVED BY J.H.G. | UNITED STATES STEEL CORPORATION APPLIED RESEARCH PITTSBURGH, PA. | FIGURE NO. 2 |
| DRAWING No ARL 18-369 | | PROJECT No 40-018-001 (31) | | |
| | | DATE 4-20-64 | | |



TRANSFORMATION DIAGRAM FOR WELD-HEAT-AFFECTED ZONE IN
5 Ni-Cr-Mo-V STEEL - HEAT NO. X53185

| | | | |
|-----------------------------------|--|-------------------------------|--------------------|
| DRAWN BY M.M. CHKOBY A.M.R. | | APPROVED BY J.H.G. | FIGURE NO. 3 |
| DRAWING NO. ARL 18-397 | | PROJECT NO. 40.018-001(31) | |
| | | DATE 4/20/64 | |

UNITED STATES STEEL CORPORATION
APPLIED RESEARCH
PITTSBURGH, PA.

WELD-THERMAL-CYCLE CONDITIONS

HEAT INPUT — 47,000 JOULES PER INCH

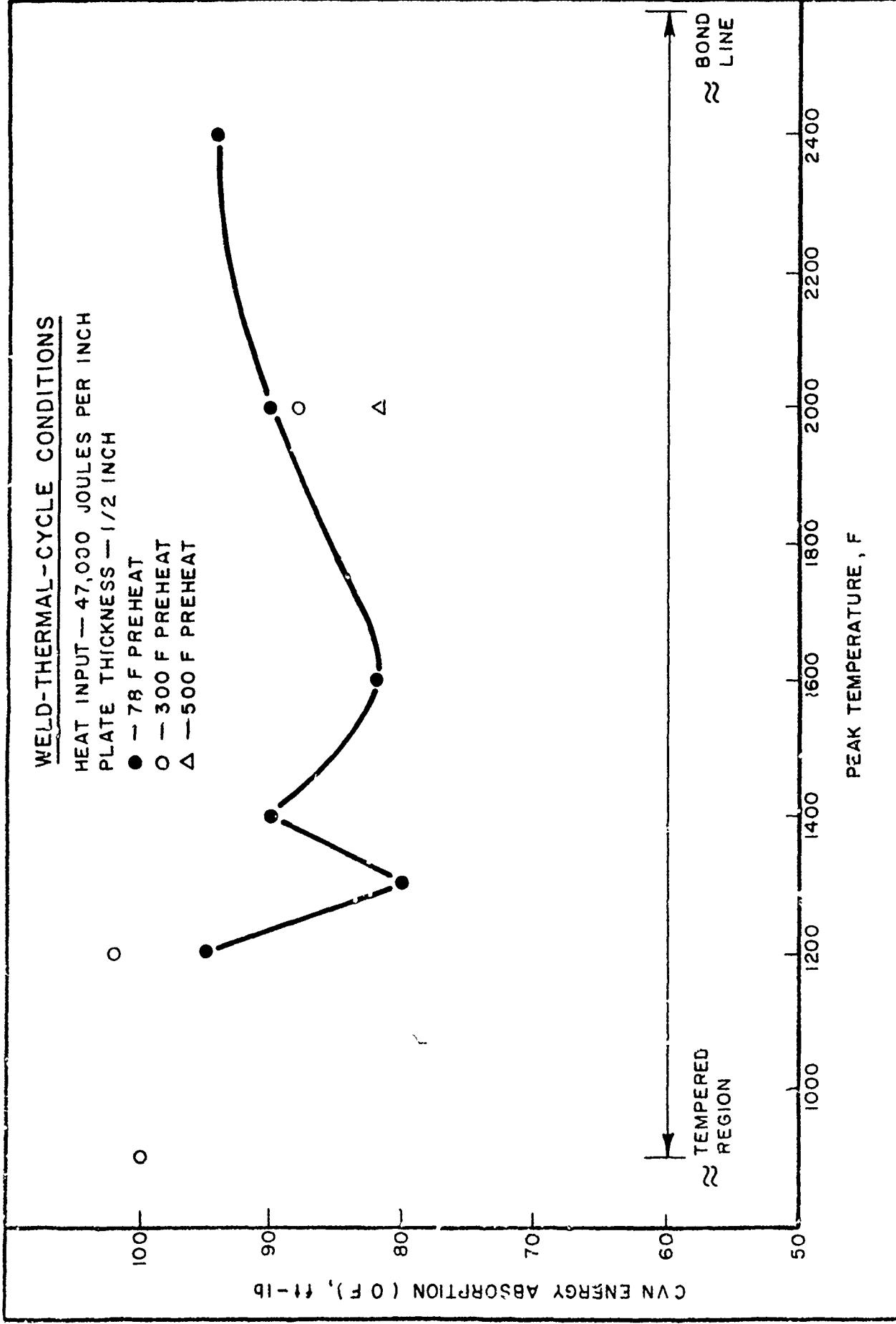
PLATE THICKNESS — 1/2 INCH

● — 78 F PREHEAT

○ — 300 F PREHEAT

△ — 500 F PREHEAT

CVN ENERGY ABSORPTION (O F), 11-1B



RELATION OF CVN ENERGY ABSORPTION TO THE VARIOUS REGIONS IN THE WELD-HEAT-AFFECTED ZONE OF 5 Ni-Cr-Mo-V STEEL (HEAT NO. X53185)

| | | | | | |
|--------------------------|--|------------------------------|-----------------------|--|--------------------|
| DRAWN BY G A Z | | CHK'D BY A M R | APPROVED BY J H G. | UNITED STATES STEEL CORPORATION APPLIED RESEARCH PITTSBURGH, PA. | FIGURE NO. 4 |
| DRAWING NO ARL 18-399 | | PROJECT NO 40 018-001(31) | | | |
| | | DATE 4-21-64 | | | |



Figure 5. Drop-weight-bulge striker and anvil.

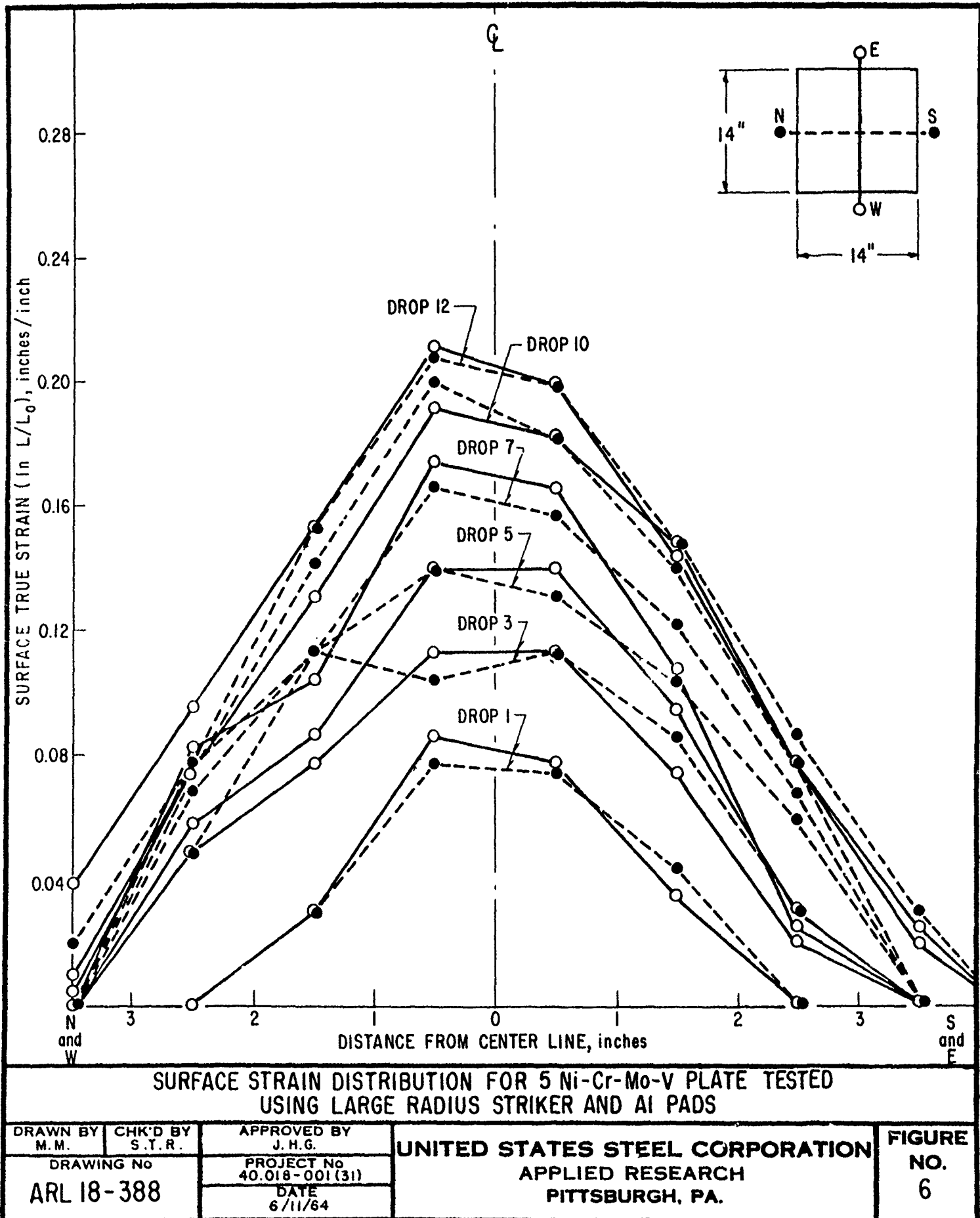
P-4225A-7

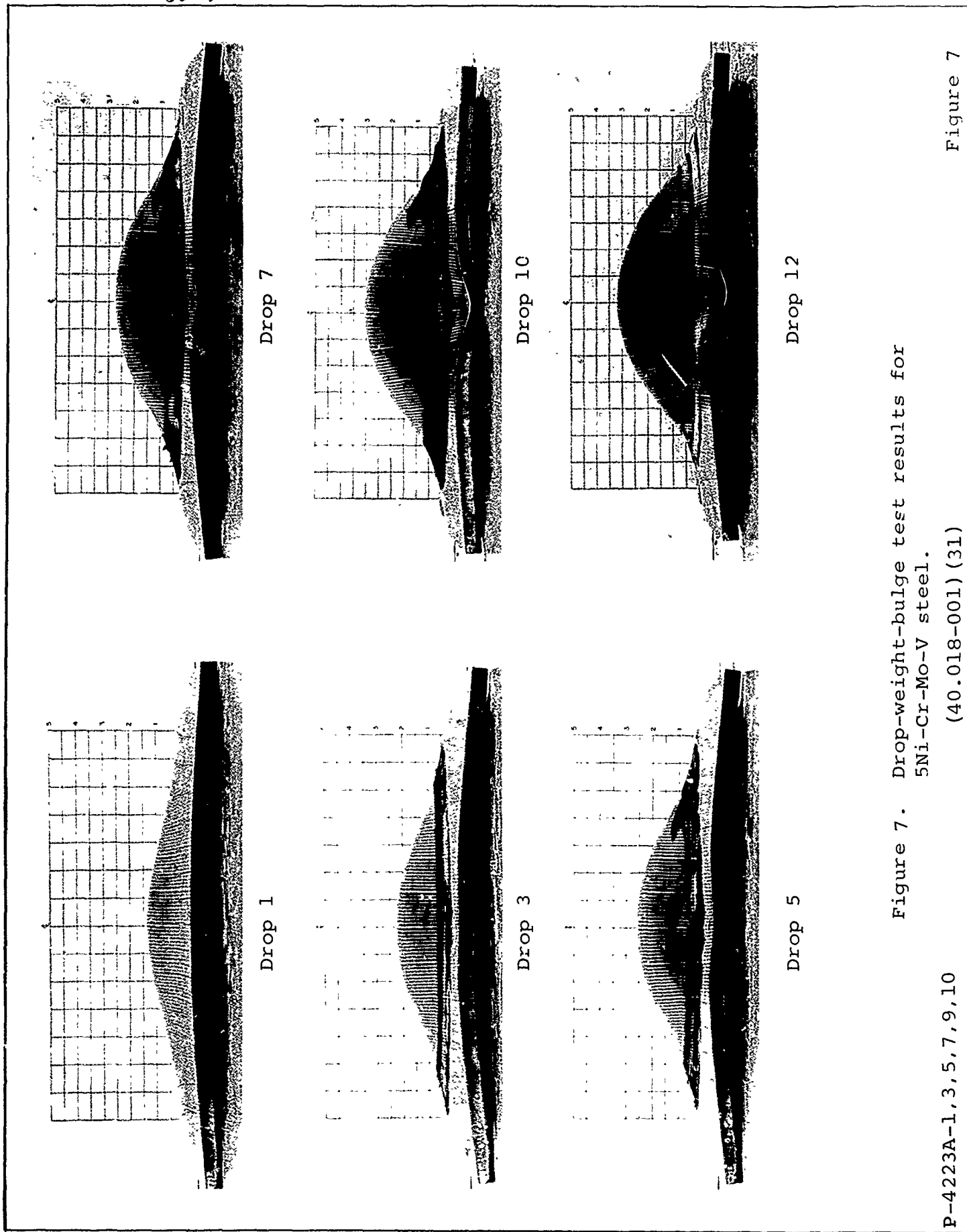
(40.018-001) (31)

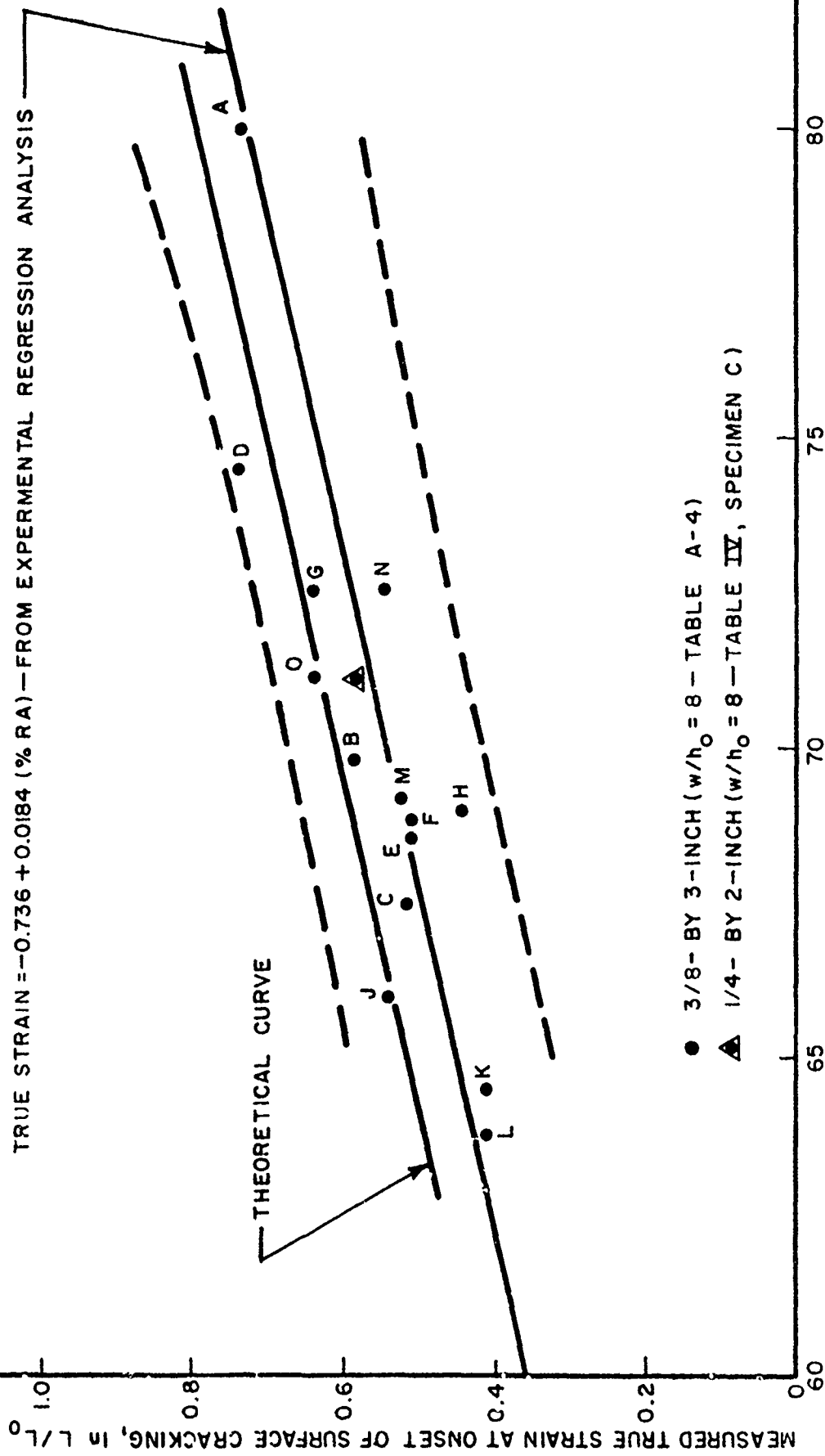
Figure 5

UNITED STATES STEEL

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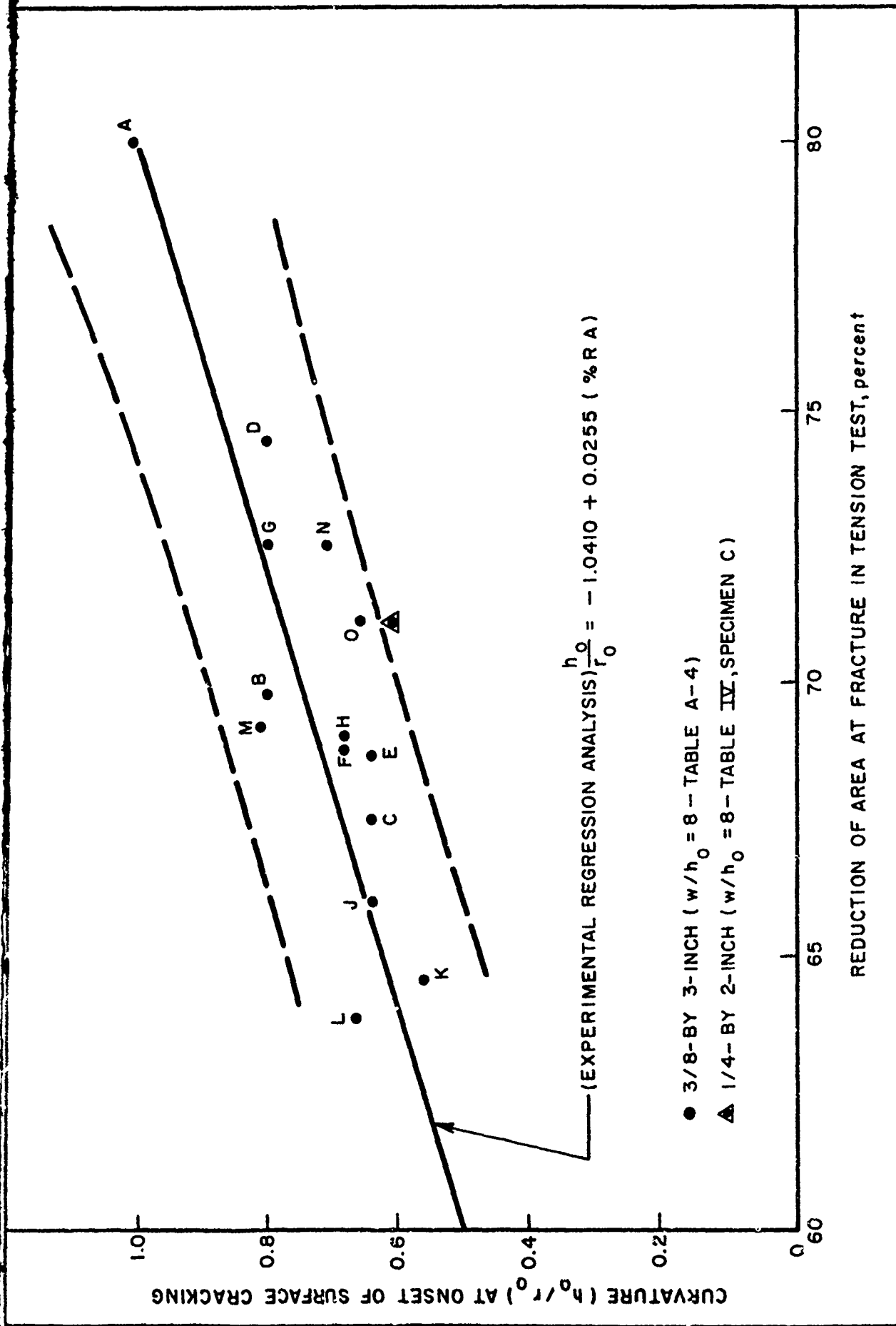


MEASURED LONGITUDINAL TRUE STRAIN AT SURFACE CRACKING IN BEND TEST
VERSUS PERCENT REDUCTION IN AREA FOR ALL STEELS

| | | |
|--------------------------|--------------------|------------------------------|
| DRAWN BY G & Z | CHK'D BY S.T.R. | APPROVED BY J.H.G. |
| DRAWING NO ARL 18-393 | | PROJECT NO 40.018-001(31) |
| | | DATE 6-16-64 |

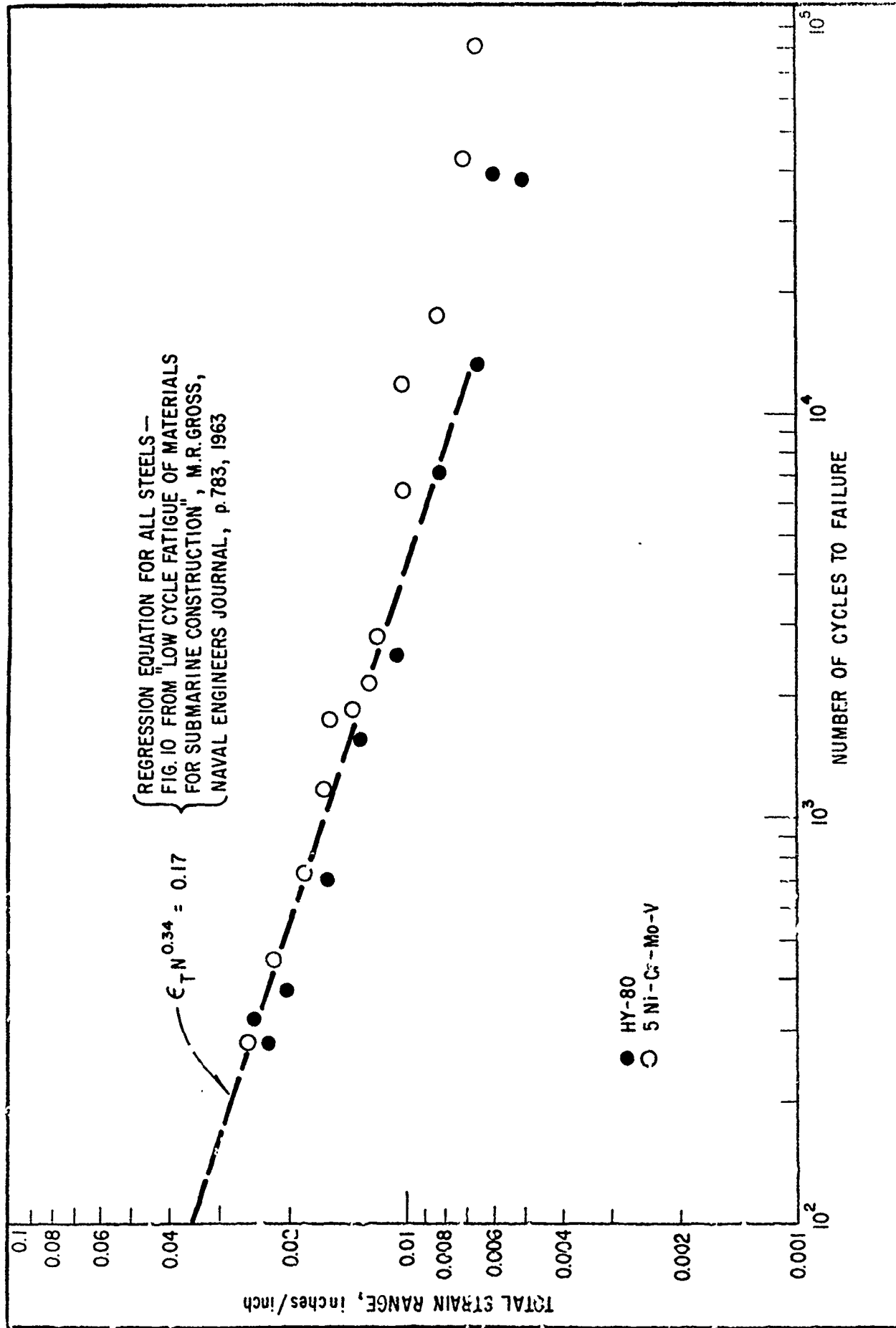
UNITED STATES STEEL CORPORATION
APPLIED RESEARCH
PITTSBURGH, PA.

FIGURE
NO.
8



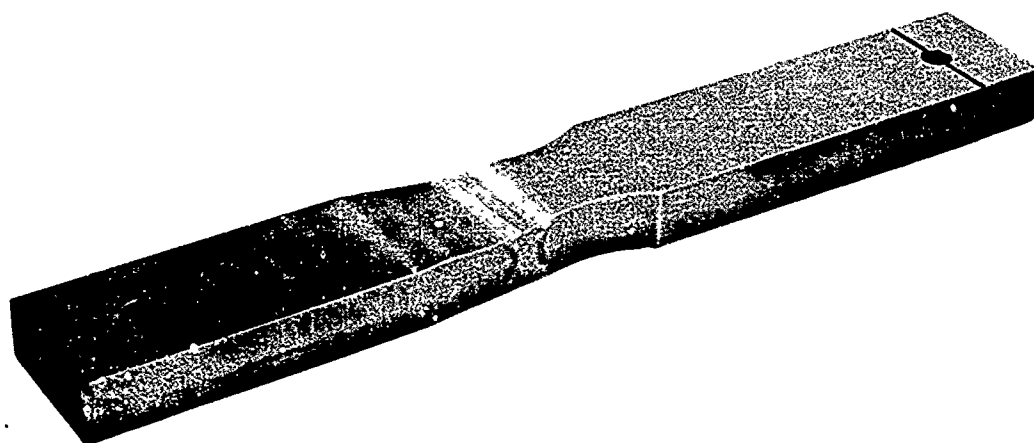
CURVATURE (h_0/r_0) VERSUS PERCENT REDUCTION OF AREA FOR ALL STEELS

| | | | | | |
|---------------------------|--|--------------------|---|--|-----------------|
| DRAWN BY G.A.Z. | | CHK'D BY S.T.R. | APPROVED BY J. H. G. PROJECT NO. 40.018-001(31) DATE 6-17-64 | UNITED STATES STEEL CORPORATION APPLIED RESEARCH PITTSBURGH, PA. | FIGURE NO. 9 |
| DRAWING NO. ARL 18-394 | | | | | |
| | | | | | |
| | | | | | |

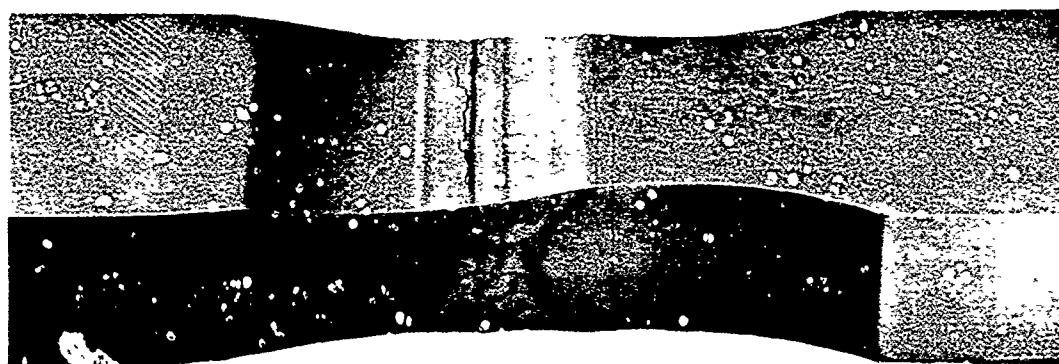


LOW-CYCLE FATIGUE RESULTS FOR 5 Ni-Cr-Mo-V STEEL AND HY-80 STEEL

| | | | | | |
|-----------------------------|--|----------------------------------|-------------------------|--|---------------------|
| DRAWN BY M. M. | | CHK'D BY S.T.R. | APPROVED BY J. H. G. | UNITED STATES STEEL CORPORATION APPLIED RESEARCH PITTSBURGH, PA. | FIGURE NO. 10 |
| DRAWING NO. ARL 18 - 415 | | PROJECT NO. 40 018 - 001 (31) | | | |
| | | DATE 7/8/64 | | | |
| | | | | | |



A. Over-all specimen (1 x 2-1/2 x 18 inches).



B. Close-up of weld showing crack location.

Figure 11. Tapered welded low-cycle fatigue specimen.

P-4340A-2
P-4340A-3

(40.018-001) (31)

Figure 11

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